DELAY SENSITIVE DELIVERY OF RICH IMAGES OVER WLAN IN TELEMEDICINE APPLICATIONS

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To Mom and Dad,

My lifelong mentors

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SUMMARY

Transmission of medical images, that mandate lossless transmission of content over WLANs, presents a great challenge. The large size of these images coupled with the low acceptance of traditional image compression techniques within the medical community compounds the problem even more. These factors are of enormous significance in a hospital setting in the context of real-time image collaboration. However, recent advances in medical image compression techniques such as *diagnostically lossless compression* methodology, has made the solution to this difficult problem feasible. The growing popularity of high speed wireless LAN in enterprise applications and the introduction of the new 802.11n draft standard have made this problem pertinent.

The thesis makes recommendations on the degree of compression to be performed for specific instances of image communication applications based on the image size and the underlying network devices and their topology. During our analysis, it was found that for most cases, only a portion of the image, typically the *region of interest* of the image will be able to meet the time deadline requirement. This dictates a need for adaptive method for maximizing the percentage of the image delivered to the receiver within the deadline.

The problem of maximizing delivery of regions of interest of image data within the deadline has been effectively modeled as a multi-commodity flow problem in this work. Though this model provides an optimal solution to the problem, it is NP hard in computational complexity and hence cannot be implemented in dynamic networks. An approximation algorithm that uses greedy approach to flow allocation is proposed to cater to the connection requests in real time. While implementing integer programming model is not feasible due to time constraints, the heuristic can

be used to provide a near-optimal solution for the problem of maximizing the reliable delivery of regions of interest of medical images within delay deadlines. This scenario may typically be expected when new connection requests are placed after the initial flow allocations have been made.

CHAPTER I

OUTLINE

The thesis is organized as follows:

1. Chapter 2 introduces the problem of wireless delivery of rich images with delay constraints. This section sets the framework for the thesis.
2. Chapter 3 examines previous work in literature in different aspects of the problem. This includes all the parameters for analysis, the system modeling and pertinent real time algorithms.
3. In Chapter 4, different concepts related to the analysis of the problem are introduced. The different WLAN systems, the notion of interactive time, the explanation of the image class and the different compression levels all discussed in this section and the concept of region of interest (ROI) of an image is introduced.
4. Chapter 5 discusses the methodology of maximizing the delivery of regions of interest of an image given a network topology. This also provides pointers on the required amount of compression to transmit the desired percentage of the image. Both complete mathematical model to solve this problem and an approximate real time solutions are presented.
5. Conclusion and key takeaways are presented in Chapter 6.

CHAPTER II

INTRODUCTION

In recent years, there has been a rapid growth in the use of wireless local area networks (WLANs). They have found their way into offices, campuses, factories, airports, coffee shops and even hospitals, providing users with freedom of movement and allowing applications to operate in a mobile environment. The profound need for mobility in our everyday application is dictating a transition from wired to wireless environments. In addition to its mobility, WLANs also enjoy cost advantage, ease of deployment, and scalability features; thus, increasingly gaining popularity with enterprises as a medium of network connection. Today, WLANs are increasingly being used for voice, data, image and video applications. However, several challenges need to be overcome if WLANs were to truly act as a replacement to wired networks. Security is a major cause for concern in enterprise applications when using WLANs. Moreover, today's wireless LAN standards fail to match the high throughput offered by their wired counterpart. Because of this, certain applications that are time-bound and require very high bandwidth are still finding this transition from wired to wireless quite challenging. A classic example of such application would be transmission of medical images for the purpose of image communication. Such image communication in a hospital would be extremely useful for collaboration on diagnosis by doctors separated by geography. The new draft standard, 802.11n, with expected offering of high throughput, seems promising in these scenarios. Typically image transmissions are considered non-real-time in nature and the sole criterion for such transmissions is the quality of the image at the receiver. However, during image communication, the latency of image delivery is of paramount importance, in addition to the image quality. These time constraints or delay bounds also known as, the “interactive time”, rather than being real time, are governed by the amount of time users are willing to wait during an interactive session. Hence, the twin measures of feasibility of such transmissions are, the received image quality and the “interactive time” (or reliability). Medical images due to their very nature, mandate lossless transmission, under all circumstances. Satisfying the stringent requirements of lossless transmission and a delay-bound for transmission of the class of medical images presents a pressing case for analysis of these scenarios.

There are two main challenges that were identified in the above context:

1. There is a need to analyze and select an appropriate wireless system that ensures lossless transmission of the class of rich images within the delay-bounds.

2. There is a need to develop an adaptive method for transmission of only regions of interest of an image to achieve desired combination of image quality and timeliness of communication.

The research examines various factors that influence successful image collaboration in the context of medical image collaboration. This includes the analysis of different wireless local area networks as a medium for collaboration. Detailed analysis of the new wireless standard, 802.11n is provided, with comparisons with the currently popular 802.11g standard. A good understanding of the sizes of the medical data and also the measure of interactive time is obtained. The different levels of lossless compression is studied for evaluation and making recommendations.

The concept of region of interest is explained and the motivation for transmitting just the regions of interest as opposed to the entire image is presented. The concept of dividing the image into three distinct regions of interest in the order of their priority is further explained with illustrations.

The thesis then models the system in order to develop an adaptive scheme to maximize the size of the regions of interest delivered to the destination within the deadline. This model uses the multi-commodity flow based approach to model the flow, interference and deadline constraints. This model is used to develop a greedy algorithm for implementation in dynamic networks.

CHAPTER III

LITERATURE SURVEY

The current articles available on networking requirements for telemedicine discuss the experience of individual organizations and institutes, which explore different telecommunication approaches from telephone lines to optical links for remote consultation. In [40], email has been used for communicating digital pathology images to the remote pathologist. Reference [41] discusses the communication requirements for telemedicine purposes indicating the use of ISDN for telediagnosis. In [42] the use of ISDN, T1 lines and an optical fiber network is suggested to provide a wide variety of bandwidth options (from 28 Kbps to 155 Mbps) depending upon the nature of the telemedicine application. Further, telemicroscopy applications has been implemented using the Internet [43],[44] and ISDN [45], to facilitate browsing of virtual slides stored on a remote server. In [15], the need for pervasive computing environment in a hospital to promote a more productive collaboration among doctors has been established. Though the paper captures the need and the high level requirements of such a system, it does not mention the implementation of such a system. An 802.11b based implementation detailed in [11] clearly brings out the need of an image transmission system in a hospital ward and describes the use of wireless system in the hospital context. Some papers [12], [13], [10], describe individual implementation of wireless systems in hospitals, but do not take delay-bound into consideration. Thus, there is a clear need for study of WLAN systems and adaptive transmission methods, in the context of medical images and hospital scenarios. WLANs have been well studied in the past few years due to its rapidly increasing popularity. [33] mentions the key concepts of WLAN system design and also several key challenges.

For applications like interactive session, human wait time becomes key towards achieving the satisfactory results [5]. This wait time is equivalent to the wait time for loading of a web page that is tolerable to users. In [9], the authors have attempted to identify how long users would wait for pages to load. This was found to be between 5 to 10 seconds depending on the importance of the data.

A detailed review of the various lossless and lossy compression schemes for medical imagery is provided in [36] and [37]. [38], [39] investigate the utility of JPEG-LS and JPEG 2000 respectively, for medical image compression. Although lossy compression schemes give much better compression ratio as compared to lossless compression schemes, the artifacts or losses introduced due to lossy compression may affect the diagnosis. Hence the general agreement in the medical community was that, only mathematically lossless compression schemes can be allowed for compression of medical images. To achieve a suitable tradeoff between compression ratio and diagnostic accuracy the concept of diagnostically lossless compression has been developed more recently [46], [21].

For delivery of maximum percentage of image within the delay bound, multi-commodity flow problem [29] has been found to be appropriate. The multi-commodity flow approach has been well studies in literature in the context of wireless networks. We build on recent works that model the routing and scheduling problem in multi-hop wireless networks as a network flow problem [23], [24], [30], [28].

In contrast to the conflict graph model [32] and edge-based approach [31], our formulation adopts a more flexible node-based interference model where interference at a given node is calculated like in [23]. However, over model tracks the state of the node rather than the state of the edge. We track interference at nodes, rather than edges, since the nodes are the physical entities in the network; performance viewed by the nodes allows more effective optimization of the network as viewed by its users. An additional advantage of the node-centric formulation is simpler distributed protocols as we directly optimize performance from the communicating nodes perspective. In [23], a node based model is described. However, they fail to take time into account while modeling.

In [22], the multi-commodity flow approach to solving the network routing problem is proved to be NP hard. This dictates the need for development of algorithm that can be implemented in dynamic networks. Several interesting algorithms have been proposed in literature to solves various issue in WLANs [25].

CHAPTER IV

PROBLEM ANALYSIS

The key objectives of the thesis are, to analyze the different 802.11 technologies, in order to achieve a good balance between the number of clients associated with an access point, the richness of the medical image transmitted, the desired delay-bound and the compression methodology used. To understand this balance, the following preliminary steps are considered:

1. Choosing the WLAN system used in an enterprise for study and analysis. These include the one that are currently popular and the next generation technologies that are likely to become popular in the near future.

2. Understanding the class of medical images and use representative images characterizing this class in the study. This would include representative sizes and also kinds of regions of interest of this class.

3. Finding the right delay-bound or interactive time for the purpose of image communication.

4. Deciding the different levels of compression to be used during analysis.

4.1 Choosing the WLAN System

[16] describes different WLAN technologies. The most popular WLANs enterprise systems in use today are based on 802.11g [2]. However, systems based on 802.11n are increasingly gaining popularity [3], [**?**], though the standard is still in the draft stage. The 802.11n standard is poised to offer great advantages in terms of higher bandwidth and range. It provides greater reliability as compared to the other existing

Table 1: Comparison between different 802.11 technologies[16]

Protocol	Release	Frequency (GHz)	Throughput (Mbps)	Data Rate (Mbps)	Modulation
802.11a	1999	5	23	54	OFDM
802.11b	1999	2.4	4.3	11	DSSS
802.11g	2003	2.4	19	54	OFDM
802.11n	2008	2.4, 5	100	300	OFDM

standards. It also promises to provide a more predictable coverage with the use of multiple spatial streams resulting in fewer dead spots.

In 2002, discussions began in the IEEE 802.11 Working Group (WG) to extend the data rates of the physical layer beyond those of IEEE 802.11a/g in order to address higher throughput wired applications that would benefit from the flexibility of wireless connectivity [34]. The key requirement that has driven most of the development in 802.11n is the capability of at least 100 Mb/s MAC throughput. Considering that the typical throughput of 802.11a/g is 25 Mb/s (with a 54 Mb/s PHY data rate), this requirement dictated at least a fourfold increase in throughput. In order to achieve this big task, the following modifications were incorporated in 802.11n.

Multiple-input multiple-output (MIMO) - MIMO is the heart of 802.11n. This allows one to transmit multiple independent data streams simultaneously to increase the spectral efficiency. This is also known as spatial multiplexing. To counter the multipath nature of the channel, OFDM coding is used along with the MIMO technology [35]. In addition to MIMO technology, 802.11n makes a number of additional changes to the radio to increase the effective throughput of the WLAN. The most important of these changes are increased channel size, higher modulation rates, and reduced overhead. Increasing from a single spatial stream and one transmit antenna to four spatial streams and four antennas increases the data rate by a factor of four. And to allow for handheld devices, the two spatial streams mode is only mandatory in an access point (AP). 40 MHz bandwidth channel operation is optional in the standard due to concerns regarding interoperability between 20 and 40 MHz bandwidth devices, the permissibility of the use of 40 MHz bandwidth channels in the various regulatory domains, and spectral efficiency. However, the 40 MHz bandwidth channel mode has become a core feature due to the low cost of doubling the data rate. Other minor modifications were also made to the 802.11a/g waveform to increase the data rate. The highest encoder rate in 802.11a/g is 3/4. This was increased to 5/6 in 802.11n for an 11 percent increase in data rate. With the improvement in radio frequency (RF) technology, it was demonstrated that two extra frequency subcarrier could be squeezed into the guard band on each side of the spectral waveform and still meet the transmit spectral mask. This increased the data rate percent over 802.11a/g vastly. An optional mode was defined with a 400 ns guard interval between each OFDM symbol to increase the data rates by another 11 percent. Another functional requirement of 802.11n was backward compatibility with 802.11a/g. This requirement was satisfied in the physical layer by defining a waveform that was backward compatible with 802.11a and OFDM modes of 802.11g. The preamble of the 802.11n mixed format waveform begins with the preamble of the 802.11a/g waveform. This includes the 802.11a/g short training field, long training field, and signal field. This allows 802.11a/g devices to detect the 802.11n mixed format packet and decode the signal field. To ensure backward compatibility between 20 MHz bandwidth channel devices (including 802.11n and 802.11a/g) and 40 MHz bandwidth channel devices, the preamble of the 40 MHz waveform is identical to the 20 MHz waveform and is repeated on the two adjacent 20 MHz bandwidth channels that form the 40 MHz bandwidth channel.

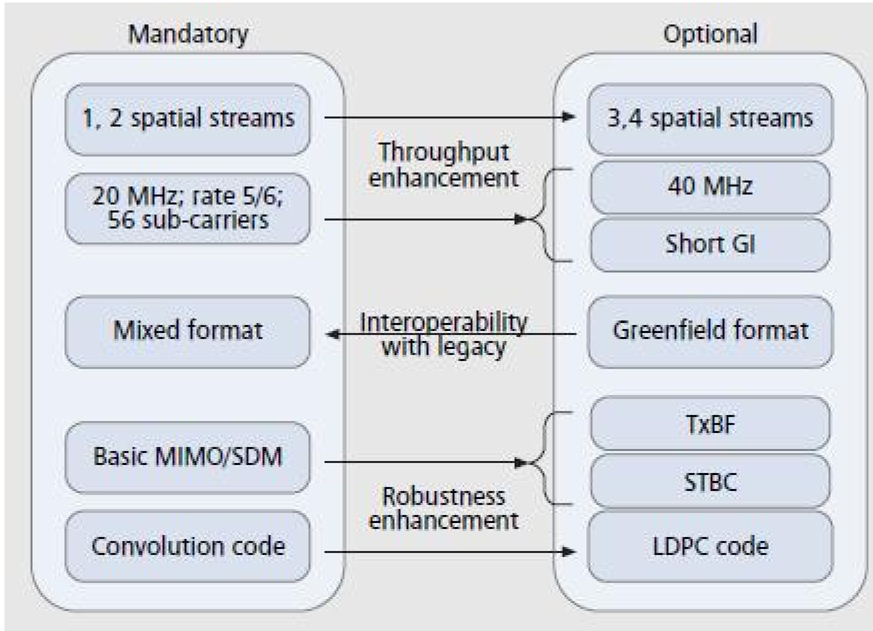

Figure 1: Physical Layer representation of 802.11n [34]

Another feature that was added to the 802.11n MAC is frame aggregation. This when used could lead to increased efficiency due to reduction in overheads. Two forms of aggregation exist in the standard: MAC protocol data unit aggregation (AMPDU) and MAC service data unit aggregation (A-MSDU). Logically, A-MSDU resides at the top of the MAC and aggregates multiple MSDUs into a single MPDU. Each MSDU is pre-pended with a sub-frame header consisting of the destination address, source address, and a length field giving the length of the SDU in bytes. This is then padded with 0 to 3 bytes to round the sub-frame to a 32-bit word boundary. Multiple such sub-frames are concatenated together to form a single MPDU. An advantage of A-MSDU is that it can be implemented in software. A-MPDU resides at the bottom of the MAC and aggregates multiple MPDUs. Each MPDU is prepended with a header consisting of a length field, 8-bit CRC, and 8-bit signature field. These sub frames are similarly padded to 32-bit word boundaries. Each sub-frame is concatenated together. An advantage of A-MPDU is that if an individual MPDU is corrupt, the receiver can

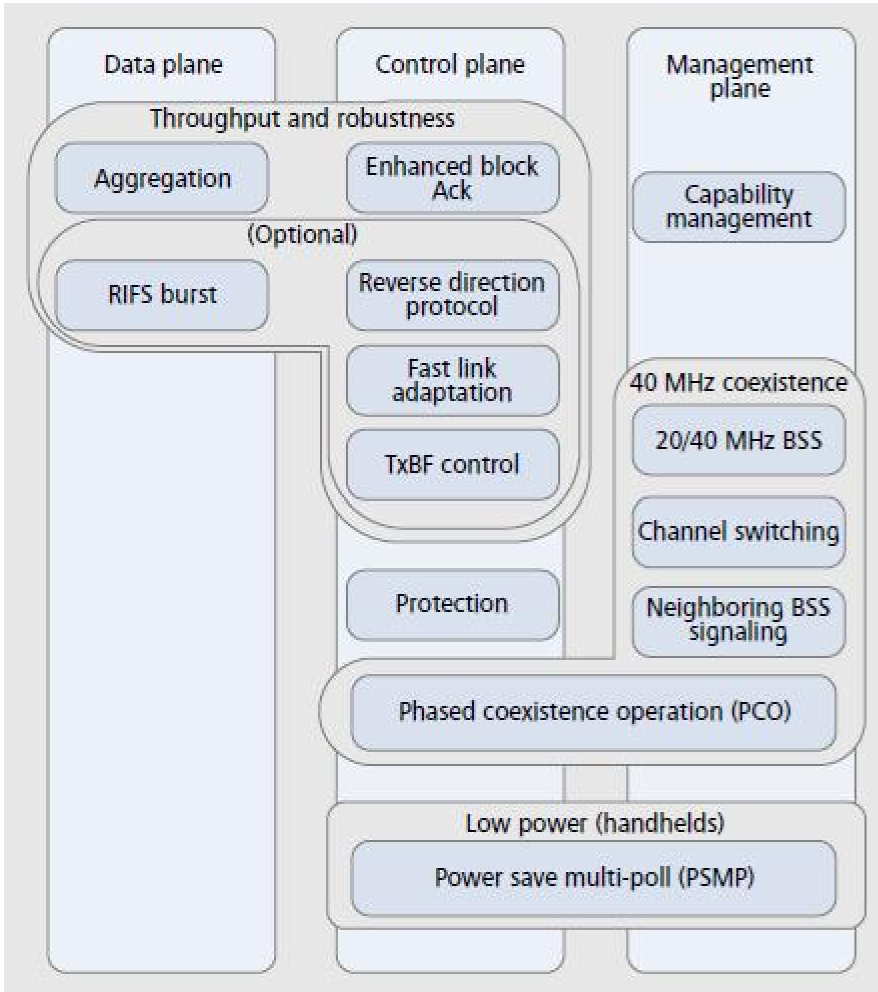

Figure 2: MAC Layer Representation of 802.11n [34]

scan forward to the next MPDU by detecting the signature field in the header of the next MPDU. With A-MSDU, any bit error causes all the aggregates to fail.

It is due to these features of 802.11n that these devices would be most suited for deployment in hospitals for the purpose of image collaboration of large medical images. The simulation results proving that is presented in the following section. Both these systems, 802.11g and 802.11n were used for the comparative study since one of them is the currently popular technology while the other is the next generation technology that is likely to become popular in the future.

4.2 Understanding the Image Class

Table 2: Size of typical medical images

Type of Image	Total Image Size per Exam
Nuclear Medicine	2MB
Magnetic Resonance Imaging	8-20MB
Ultrasound (Color)	5-8MB
Digital Angiography	15-24MB
Digitized Electron Microscopy	5-8MB
Digitized Color Microscopy	15-24MB
Computer Tomography	20MB
Computer Radiography	8-32MB
Digitized X Rays	8MB
Digitized Mamography	64MB
Cardiac Catheterization	500-1000MB
Spiral or Helical CT	40-150MB

Medical images are at the heart of the healthcare diagnostic procedures. They have provided not only a noninvasive mean to view anatomical cross-sections of internal organs, tissues, bone and other features of patients but also a mean for physicians to evaluate the patient's diagnosis and monitor the effects of the treatment, and for investigators to conduct research of the underlying disease. The class of medical images is extremely diverse [20] [19]. Most commonly used images for diagnostics are medical resonance imaging (MRI), computerized tomography (CT), ultrasound, cardiac catheterization, digitized mammography, x-rays among others. Consider a single study of CT scan of thirty 512 x 512 x 16 bits images; each examination is approximately 15 megabytes. And for digital mammography study of four 4K x 6K x 12 bits, the amount of data grow to 200 megabytes per examination. For the Clinical Center, it is estimated that approximately 8 million individual image slices are generated per year. This is equivalent to eight terabytes of image data assuming a typical individual image size is 1 megabyte. DIACOM images have not been specifically considered for analysis in this work. However, the body of work can be easily extended to cater to those images as well. These different types of images can be categorized into three groups, those ranging close to 10MB like CT, those around 100MB for digital mammography, and almost 1000MB for cardiac catheterization. Table 2 lists the different types of medical images. These different images have completely different characteristics in terms of network demands during an image communication session. The thesis evaluates the network needs of these three distinctive image classes during an interactive session in order to make recommendation for suitably handling these images.

4.3 Setting the "Interactive Delay-Bound"

For applications like interactive session, human wait time becomes key towards achieving the satisfactory results [5]. This wait time is equivalent to the wait time for loading of a web page that is tolerable to users. In [9], the authors have attempted to identify how long users would wait for pages to load. Users were presented with Web pages that had predetermined delays ranging from 2 to 73 seconds. While performing the task, users rated the latency (delay) for each page they accessed as high, average or poor. Latency was defined as the delay between a request for a Web page, and totally receiving that page. They reported the following ratings: High (good): Up to 5 seconds, Average: From 6 to 10 seconds, and Low (poor): Over 10 seconds. The results from this study will be incorporated in the proposed research to set delay bounds known as "interactive time" for transmission of medical images over the WLAN. The interactive time is thus set as having a value of ideally less than 5 seconds.

4.4 Exploring Compression Levels

Typical compression scheme like JPEG and JPEG 2000 are lossy. These lossy compression schemes can introduce artifacts, which when used in the context of medical

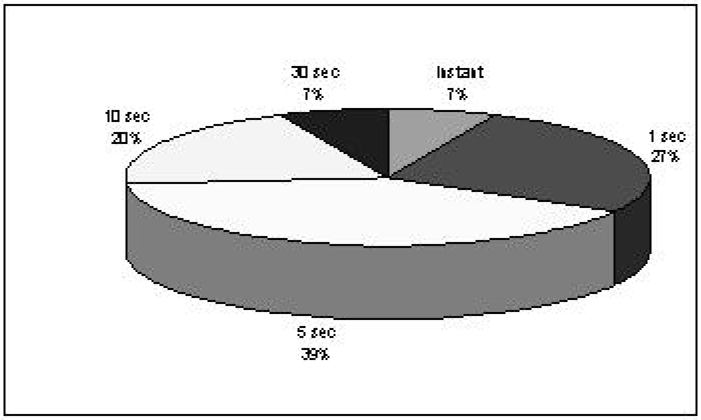

Figure 3: Average time users are willing to wait during an interactive session [9]

images, result in incorrect diagnosis. Hence, it is advisable to archive any medical images with no compression or utmost mathematically lossless (ML) compression. Mathematically lossless compression schemes allow perfect reconstruction after decompression of the compressed image and hence no objectionable losses/artifacts are introduced. Mathematically lossless compression schemes give a very low compression ratio (of the order 2:1), making them unattractive for transmitting larger image files under network and delay constraints. To allow higher compression, while ensuring diagnostic accuracy prompted development of the criterion of diagnostic losslessness (DL). In [21], the image quality measurement criterion of diagnostic losslessness was introduced. Here, 8 images (formalin-fixed paraffin-embedded tissue sections) were acquired and compressed using JPEG at compression ratios varying from 15:1 to 22:1 and presented to a combination of surgical pathologists and pathology residents at Emory University. The results concluded that images can be compressed using JPEG at diagnostically lossless compression ratios of the order 10:1 to 20:1 depending on the input image. Diagnostic losslessness was introduced as a measure based on *subjective testing by experts, which allows compression beyond ML as long as the introduced artifacts do not disturb the diagnosis*. Clearly, in cases where bandwidth is a major constraint and the image sizes are very big it can be a very promising alternative. In this research, medical images compressed to varying levels will be analyzed based on its meeting the “interactive time-bound” for different WLAN systems.

4.5 Results

The thesis research makes an attempt to find an optimized solution to the problem of transmission of medical images within the constraints described in this section by understanding the bounds in each case and also additionally finding adaptive mechanisms [14] of effective image delivery for image communication purposes.

The WLANs were simulated in ns2 in the infrastructure mode with the AP supporting from 2 to 20 clients. The setup consisted of infrastructure mode with a wired backhaul and a wireless cluster. The wireless cluster consisted of AP with multiple clients. The transmission setup was essentially a 2-hop network. The parameters of the channel and MAC were modified according to the standards. While modeling 802.11n, additional features like Block ACKs and frame aggregation was incorporated in addition to changing the PHY and MAC parameters. Since reliability of data was of primary concern, TCP was the transport layer of choice. Absence of wireless link failures was assumed during simulations.

TCP aggregate throughput was calculated for three setups - 802.11g, 802.11n with no frame aggregation and 802.11n with packet aggregation. Figure 4 shows the results obtained from the simulation of aggregate throughput with increasing number of clients associated with the AP. *Throughput is the average rate of successful data delivery over a communication channel. Aggregate throughput is the sum of the data rates that are delivered to all terminals in a network* [1]. The TCP aggregate throughput was calculated using the relation 1

$$AggregateThroughput = TotalBytesReceived/TotalSimulationTime \qquad (1)$$

Next, the average delay for transmission between two clients was calculated at the receiver. This test was carried for multiple scenarios each with increasing number of

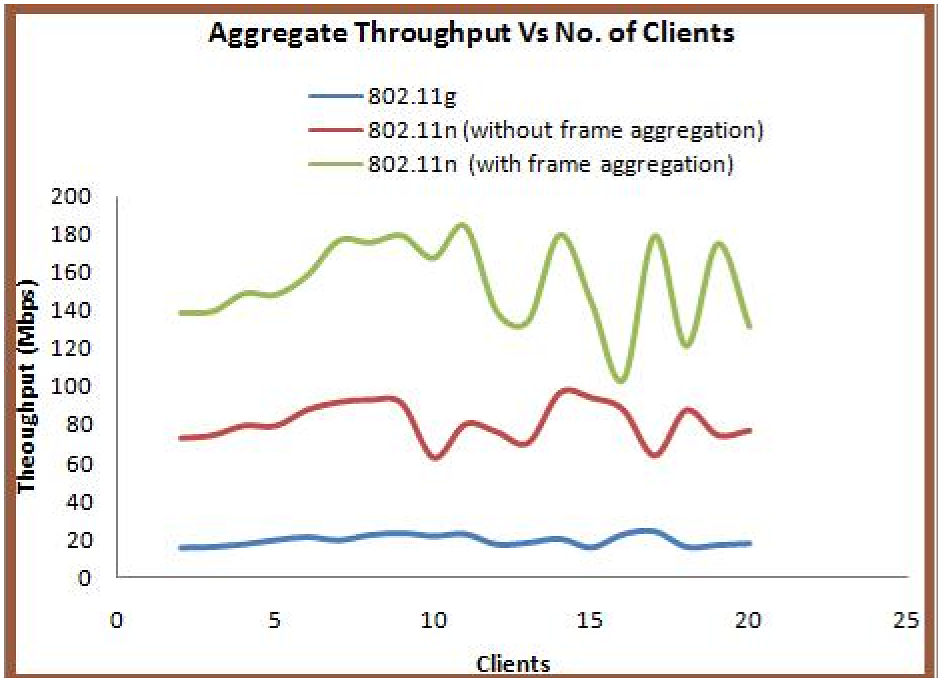

Figure 4: Aggregate throughput with increasing number of clients for different WLANs

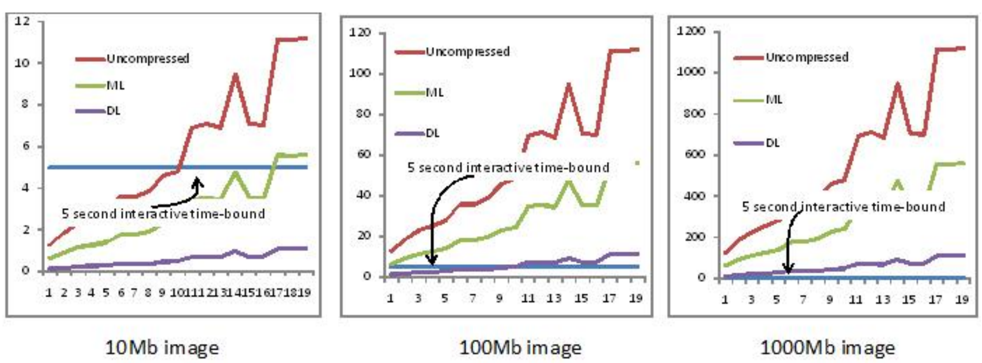

Figure 5: Average delay Vs. No. of clients for 802.11g system

transmission in the system. The aggregate average delay for each of the test scenarios was calculated. The maximum number of clients that could be supported by an AP for each of the WLAN system for transmission of images within the delay bound was calculated for different levels of compression. Figures 5, 6 and **??** show the results of the simulation.

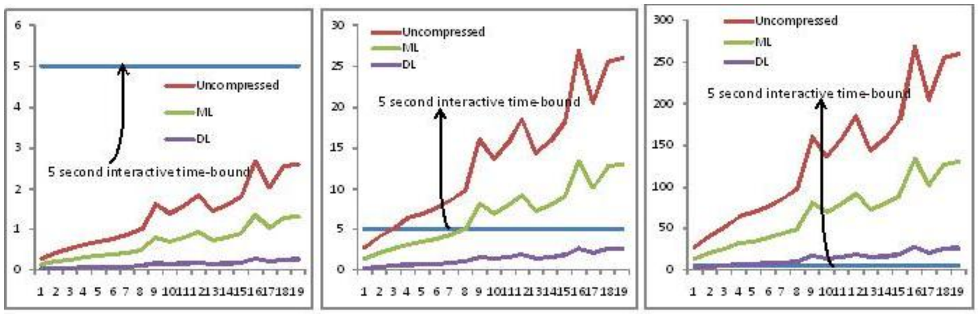

Figure 6: Average delay Vs. No. of clients for 802.11n system with no frame aggregation

4.6 Region of Interest

We notice that for the class of image of size of 10MB, 802.11g system was found to be suitable even without any compression with simultaneous transmission of the same sized images by about 17 clients supported within the delay bound of 5 seconds. However, for a 100MB sized image, 802.11g WLAN could be used with ML and DL compression level with 9 simultaneous image transmissions supported with ML compression and much more with DL. On the other hand, 802.11n was found to be suitable for this class of images with ML compression or even no compression if frame aggregation is done at the MAC. For the class of images of range 1000MB however, DL compression performed on images and the use of 802.11n for transmission with frame aggregation done at MAC was found to be most suited. Simultaneous image transmission by 9 clients, all transmitting images of this size was found be within acceptable delay bound.

The results of the simulation were all obtained for a two hop network. This shows that for large image sizes, even with maximum possible compression, the delivery of the entire image under consideration within the “interactive time“ is a challenge. To make the problem more manageable, the image can be divided into three distinct regions of interest with different priorities.

The region with highest priority would be given the maximum weight during the

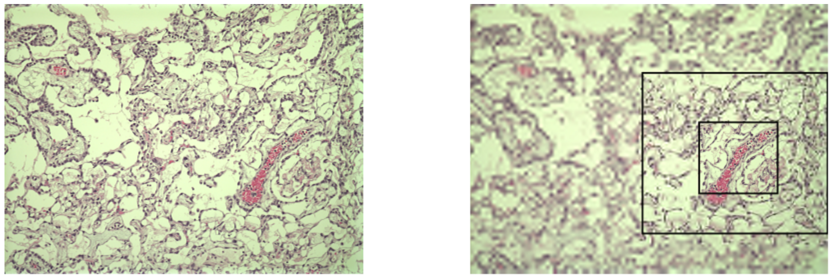

Figure 7: (a) Original Image (b) Three Regions of Interest

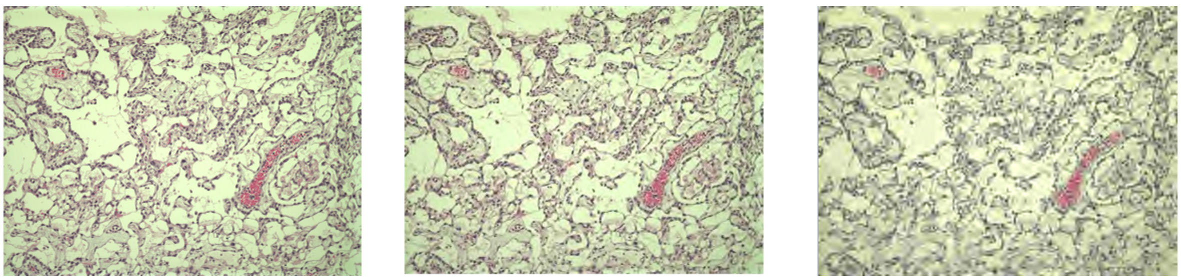

Figure 8: (a) ROI 1 level of compression (b) ROI 2 level of compression (c) ROI 3 level of compression

transmission. Let this region be denoted as region I. These regions are typically those that are of maximum importance to the physicians. Hence these regions could also have least amount of compression performed to maintain the integrity of the content. Typically such image would be compressed using ML compression technique or in some cases not compressed at all. Both the size and the compression ratio of this region would depend on the network topology and the interactive time.

The region with the next highest priority are the pixels that are adjacent to region 1. This region can be denoted as region 2. These regions often have peripheral information that though not critical for diagnosis, provide the supplementary information to the physician. These regions could be compressed at a much higher rate. DL compression can be used in this instance.

The region with least priority are the background pixels. These can be denoted as region 3. These have information that may or may not be transmitted. Even when transmitted, this region can be compressed with a high degree of compression.

The image data delivery to the destination is a function of the network conditions, the delay tolerable, and the compression ratio used. This could be further mapped as a function of the size of different regions of interest and their weights.

$$image\ size\ delivered = f(network\ conditions, interactive\ time, compression) \quad (2)$$

This could be further mapped as a function of the size of different regions of interest and their weights. If $w_1, w_2, and\ w_3$ are the weights for regions 1, 2 and 3 respectively such that $w_1 >> w_2 >> w_3$,

$$image\ size\ delivered = w_1 \cdot ROI_1 + w_2 \cdot ROI_2 + w_3 \cdot ROI_3 \quad (3)$$

CHAPTER V

PROPOSED SOLUTION

5.1 System Model

Initial feasibility studies have suggested that transmitting rich medical images for the purpose of image collaboration within the delay bound would involve transmitting only regions of interest of the image as opposed to the entire image. A key challenge in this context would be to identify the fraction of the original image that forms a part of the region of interest to be transmitted. These can then be either transmitted in the uncompressed form or compressed form based on the requirements.

Image collaboration can be modeled mathematically as a generalization of multi-commodity network flow problem where each connection between source and sink corresponds to a commodity. The initial problem is routing of these commodities within the tolerable delay. Interference between nodes is considered while modeling. The solutions presented in this paper are globally optimized for a time expanded network. We assume that all the details of the problem including the topology and capacity of the network as well as all the connection details are provided to us prior to time period of interest so that the entire scheduling can be computed. The solution thus cannot be deployed in dynamic networks directly. However, these can form the basis for developing distributed algorithms for use in a dynamic network.

5.1.1 Problem Formulation

Let N denote the set of all the nodes in the network where $N = \{n_i\}$ and $|N| = \text{n}$. A node m can directly transmit to another node n if the quality of the signal received by n is above a given threshold. We denote such tuple of nodes (m, n) as an edge. Let E be the set of all edges such that $E = \{e_i = (h_k, t_l) | h_k, t_l \in N\}$. The directed graph for such a network is $G = (N, E)$.

The nodes represent the mesh aggregation device or the access points. These mesh aggregation devices provide network connectivity to end-user mobile wireless devices within their coverage area by collecting and forwarding their traffic to mesh gateways connected to the wired network. The topology of the network is considered to be static and packets for a particular connection may flow through multiple intermediate wireless links. Furthermore, we assume that each node has sufficient buffer to store any received content for transmission at a later time.

We assume that when a transmission occurs on a link, nodes in the vicinity of the transmitting and the receiving nodes are prevented to transmit or receive. This eliminates any issues of interference by nodes within the interference range of the transmitting node. For any given transmitting node i, let $R(i)$ represent the set of nodes that are within the receiving range, and let $I(i)$ represent the set of nodes that are expected to experience interference. This data could also be represented as two $n\mathbf{x}n$ matrices. Typically $R(i)$ is a subset of $I(i)$ and the two matrices are symmetric.

Each image, rather than being transmitted as a whole is often transmitted as units of data. Each data unit transmitted from a source to a sink is considered as one connection. In other words, each connection in the original problem gives rise to as many connections as the number of data units in an image in our model. These data units could either consist of a single packet or aggregation of multiple packets. In this model the number of connections for each commodity is the number of packets to be transmitted. Let q' be the size of the total image to be transmitted, and let the size of each data unit be p, then the number of data units per image is $\lceil q'/p \rceil$. Let this be represented as q. The capacity of each node is assumed to be constant. Let the capacity of the nodes be U. The unit time interval t is thus a function of the node capacity and the size of the data unit (consisting of one or more packets). This model enables us to discretize time as intervals given by the equation:

$$t = p/U \tag{4}$$

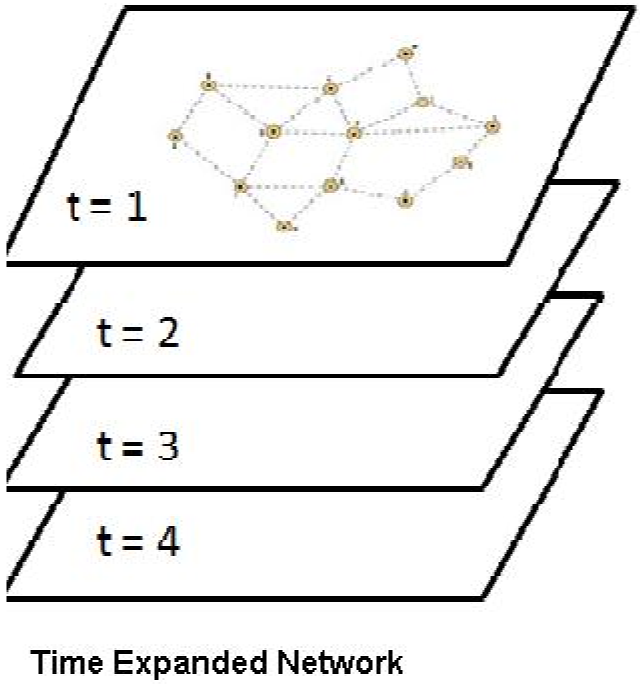

Figure 9: Time expanded network

Let $C = \{c_i\}$ represent the set of all possible connections in the network. We consider the scenario where the content of size q may be available for fetching from any of the multiple source nodes by any of the destination nodes, with each destination node having a deadline. In other words, each element c_i of C can be represented as (S_i, D_i, T_i) where $S_i = \{s_1^n, s_2^n, s_3^n, ...s_s^n\}, D_i = \{d_1^n, d_2^n, d_3^n, ...d_d^n\}, T_i = \{t_1^n, t_2^n, ...t_d^n\}$. Here S_i denotes the set of all source nodes for the connection, D_i denotes the set of all destinations for the connection, T_i represents the deadline for each destination. The multi-source, multi-sink problem can be transformed into single-source, single-sink problem by adding a super-source and super-sink. These scenarios are discussed in detail in section 5.1.1.7.

We define two boolean variables $x_i^{n,t}$ and $y_i^{n,t}$, for each connection n, node i and starting at time t. $x_i^{n,t}$ is 1 if the node i of connection n at t is transmitting data or 0 otherwise. Similarly $y_i^{n,t}$ is 1 if the node i of connection n at t is receiving data or 0 otherwise.

$$x_i^{n,t} = \{ \begin{array}{ll} 1 & \text{if node } i \text{ is transmitting commodity } n \text{ at time } t \\ 0 & \text{otherwise} \end{array} \tag{5}$$

$$y_i^{n,t} = \{ \begin{array}{ll} 1 & \text{if node } i \text{ is receiving commodity } n \text{ at time } t \\ 0 & \text{otherwise} \end{array} \tag{6}$$

With the above framework in mind, we model the system by applying necessary constraints to achieve the objective of maximizing the image delivery within the specified delay bounds (or deadlines). We first analyze the behavior of each node in isolation to develop the flow constraints. Next, we analyze the effect of the node behavior due to its neighborhood to develop interference constraints. We then tie the time constraint in the model to analyze multi-commodity flow over time.

5.1.1.1 Flow Constraint

The busy time of the node can be split into Signal (when receiving and transmitting) and Interference (the silent period of a node to enable the neighboring flows). Thus a particular node i in the network graph $G = (N, E)$ can either be productive (by transmitting or receiving a signal) or be silent (due to interference) or be idle (due to under-utilization of the network).

A particular node can transmit only one commodity at a particular instant of time.

$$\sum_{n \in C} x_i^{n,t} \leq 1 \qquad \forall i, t \tag{7}$$

Similarly, a node can only listen to one commodity at a time. This is represented mathematically as

$$\sum_{n \in C} y_i^{n,t} \leq 1 \qquad \forall i, t \tag{8}$$

A particular node cannot transmit and listen simultaneously. This constraint is represented mathematically as

$$x_i^{n,t} \cdot y_i^{n,t} = 0 \qquad \forall i \in N, t, n \in C \tag{9}$$

The flow constraint in this model reduces to

$$\sum_{n \in C} x_i^{n,t} + \sum_{n \in C} y_i^{n,t} \leq 1 \qquad \forall i, t \tag{10}$$

Please note that equation 10 automatically implies equations 7, 8 and 9.

5.1.1.2 Interference Constraint

For every node $i \in N$, let $I(i)$ represent the interference vector of i where column $j \in I(i)$ is 1 if j is within the interference range of i. There are two interference models that are discussed in literature, the receiver conflict avoidance (RCA) model and transmitter-receiver conflict avoidance (TRCA) model. According to RCA, for reception to be successful, all other transmitting nodes that can potentially interfere with the receiver must remain silent. In case of TRCA, for successful transmission to occur, the neighbors of the transmitter and the receiver have to refrain from both transmitting and receiving for the duration of the transmission. For our model we would be considering RCA. Extending this to TRCA could be a part of future work. Equation (11) is a representation of this constraint.

$$|I(i)|.x_i^{n,t} + \sum_{j \in I(i)} x_j^{n,t} \leq |I(i)| \qquad \forall i, n, t \tag{11}$$

In this equation, when node i is transmitting, all the other variables are forced to zero. However, when node i is not transmitting, no restriction is imposed on its neighbors, as expected.

5.1.1.3 Range Constraint

In order for a node i to receive a particular commodity n at time t, there must exist another node in its reception range that is transmitting the same commodity at time t. This is bound by the constraint in equation (12)

$$y_i^{n,t} \leq \sum_{j \in R(i)} x_j^{n,t} \qquad \forall i, n, t \tag{12}$$

5.1.1.4 Time constraint

For every node i that is transmitting commodity n at time t, unless it is the source node, it should have received the commodity prior to this transmission.

$$x_i^{n,t} \leq \sum_{a<t} y_i^{n,a} \qquad \forall i \notin S_i^n, \forall n, t \tag{13}$$

5.1.1.5 Objective Function

The objective of the problem is to maximize the number of weighted packets received at the destination nodes within their respective deadlines.

$$Maximize \sum_{n \in C} \sum_{d_i^n \in D_n} \sum_{a<t_i^n} w^n y_{d_i^n}^{n,a} \tag{14}$$

5.1.1.6 Source and Sink nodes

The discussion so far in this paper have dealt with source and destination access points. In order to include the individual clients in discussions, we add an extra node for every source and sink node in our original model. These source and destination clients can only communication with the access points they are associated with. Hence the interference set $I(i)$ and range set $R(i)$ of these nodes reflect the fact that the source and destination clients are in the range of only their corresponding access points.

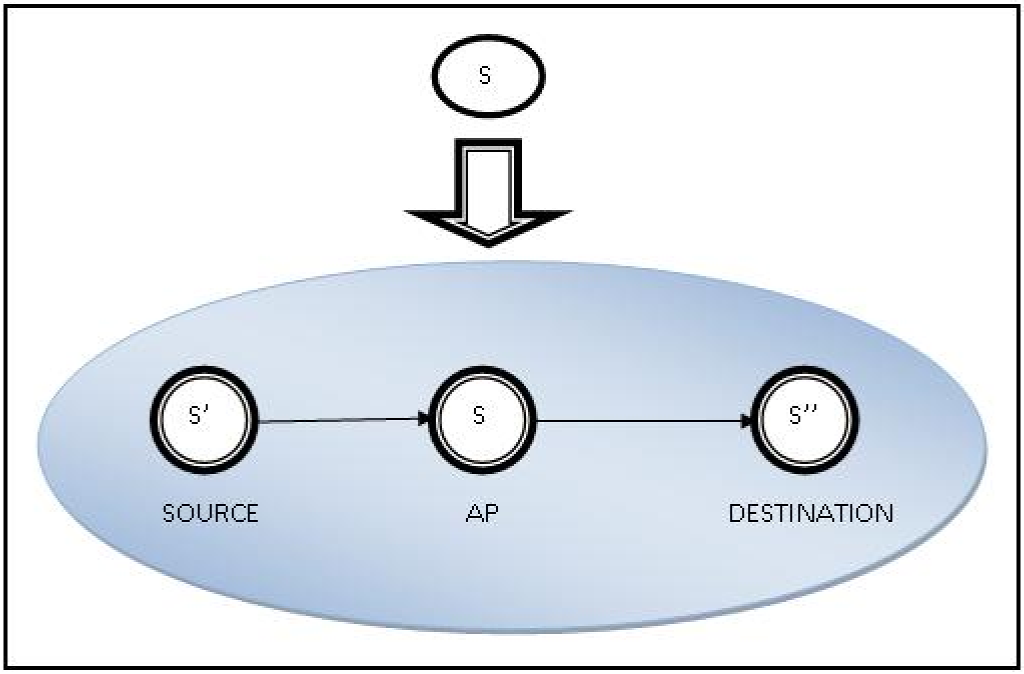

Figure 10: Node expanded to accommodate source and sink

5.1.1.7 Multisink case

Image communication applications typically consist of a single source and multiple sinks. In certain cases, several copies of these images may be present at multiple sources as well. In such scenarios, these different sources are combined to form single super-source. The capacity of the link from the super-source to client-source is considered infinite. Multi-sink is converted into single sink only if all the different sinks for a commodity have the same deadline. All the sinks that have the same deadline could be linked together. Our generalized model in the previous sections can model the behavior of multiple source, multiple sink without adapting them into single source and single sink.

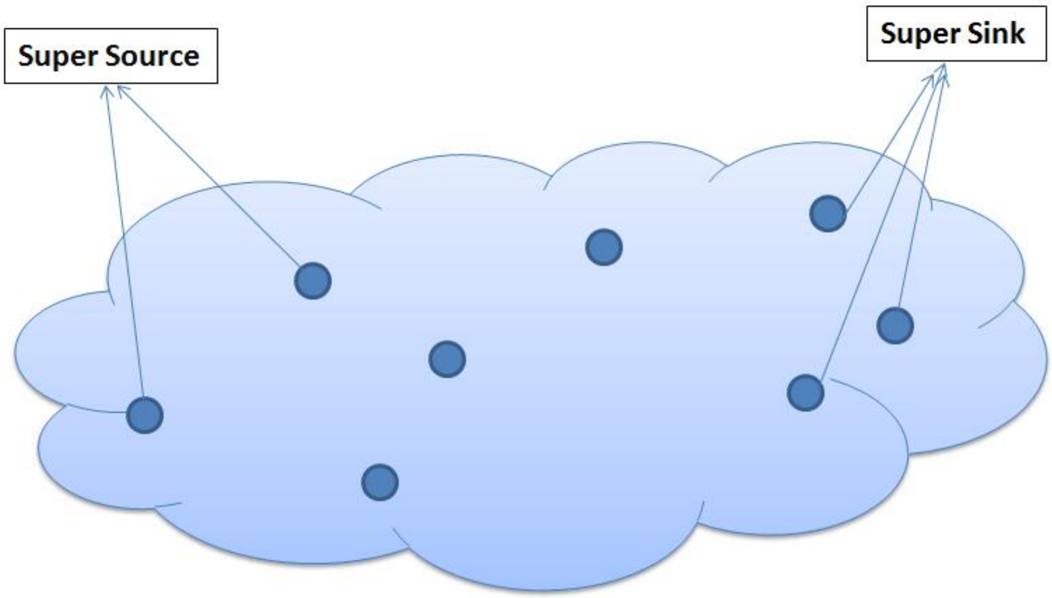

Figure 11: Super source and super sink

5.1.2 Extension of Multi-Commodity Flow Formulation to Multi-Channel Case

The single channel model can be transformed into a multichannel by some minor modifications. Let K = k represent the set of orthogonal channels. Then $x_i^{n,t}$ and $y_i^{n,t}$ will transform to $x_{i,k}^{n,t}$ and $y_{i,k}^{n,t}$ for each channel k.

5.1.2.1 New Flow Constraint

The flow in one channel is independent of another hence the flow constraint must be met in all the channels. The flow constraint in this model reduces to 15.

$$\sum_{n \in C} x_{i,k}^{n,t} + \sum_{n \in C} y_{i,k}^{n,t} \leq 1 \qquad \forall i, t, k \tag{15}$$

5.1.2.2 New Interference Constraint

The interfering nodes in one channel do not affect those in other channels. the interference constraint thus reduces to 16.

$$|I(i)|.x_{i,k}^{n,t} + \sum_{j \in I(i)} x_{j,k}^{n,t} \leq |I(i)| \qquad \forall i, n, t, k \tag{16}$$

5.1.2.3 New Range Constraint

Since the transmitting and receiving nodes must be in the same channel, the range constraint becomes 17.

$$y_{i,k}^{n,t} \leq \sum_{j \in R(i)} x_{j,k}^{n,t} \qquad \forall i, n, t, k \tag{17}$$

5.1.2.4 New Time Constraint

Since a non-source node i should have received the commodity from another node from any of the channels, the time constraint reduces to 18.

$$x_{i,k}^{n,t} \leq \sum_{k \in K} \sum_{a<t} y_{i,k}^{n,a} \qquad \forall i \notin S_i^n, \forall n, t \tag{18}$$

5.1.2.5 Channel Constraint

A particular node can either transmit or receive only one commodity at a particular time irrespective of the number of channels supported.

$$\sum_{k \in K} x_{i,k}^{n,t} + \sum_{k \in K} y_{i,k}^{n,t} \leq 1 \qquad \forall i, t, n \tag{19}$$

5.1.2.6 Objective Function

The objective of the problem is to maximize the number of packets received at the destination nodes within their respective deadlines.

$$Maximize \sum_{k \in K} \sum_{n \in C} \sum_{d_i^n \in D_n} \sum_{a<t_i^n} y_{d_i^n}^{n,a} \tag{20}$$

5.2 Heuristic

The system modeling explained in the previous section provides an optimal solution to the problem. However, since its computational complexity is NP hard, it cannot be used in dynamic networks. To find solutions to networks that have connection requests generated at an instant of time after the system model has provided the initial solution, we propose a fast approximation algorithm to maximize the number of image data packets that are delivered to the their destinations before their respective deadlines. The scenario that the algorithm models is when a new connection request is placed in a network where the connections have already been scheduled and the network is carrying traffic.

We model this algorithm with one source and multiple destinations for each connection. As with the mathematical model, we use a time-expanded network, where the time slices are chosen so that we find the right balance between computational complexity and approximation induced sub-optimality. The topology of the network is assumed to be known before the start of the algorithm. The interference model used in the network is based on TRCA [31]. The neighbors of the transmitter and the receiver have to refrain from both transmitting and receiving for the duration of the transmission. In order to capture this we construct an interference matrix of the network to mimic this behavior. The assignment of values to the interference matrix is done dynamically as the data transmission occurs. This interference matrix is an important metric to denote congestion.

Though the topology of the node is assumed to be random, this can be easily transformed into a Manhattan grid by marking the holes in the grid as nodes with interference (or congestion) for all time values. This transformation is valid since these nodes cannot be used for hopping to the destination. Transformation of a random topology into a grid helps in exploiting the geometry of the network in developing the algorithm. The connection related information like the position of source and the destinations, the size of data used for image collaboration and the priority (or weight) of the connection is known at the beginning of each connection. With these assumptions in place the algorithm has the following steps.

5.2.1 Sorting the Connections

When a number of connection requests are placed at a particular instant of time, the order in which these connections are serviced is based on a combination of factors. Weight or priority assigned to the connection is a very important metric. Higher the weight of the connection, more likely are the chances of it getting picked to be serviced and hence it is accorded higher preference while sorting. Minimizing hops and distributing the load fairly over the network by avoiding congestion are important as well. In order to achieve this connection with lower number of hops is accorded greater preference that the one with higher number of hops. However, in certain cases, when the connection with lower number of hops is in an extremely congested, the connection with greater number of hops, but in a lower congestion region should be accorded higher preference. Thus, in certain cases there might be a trade-off required between hop count and load distribution. In addition, since our heuristic algorithm is meant for real-time applications, deadlines play a major role in our sorting algorithm. Though intuitively, connections with shortest deadlines would gain highest preference, when the network has limited capacity, it may be prudent to allocate the connections with more liberal deadline so that we are not using computational time in trying out allocating tasks with stringent deadlines. Hence there is a trade off required in giving preference to a connection that has a deadline long enough to meet the deadline constraint versus to a connection that with a small deadline so that starvation of that connection does not occur.

5.2.2 Complete Time Expanded Graph

1. The topology of the network in the form of a manhattan grid is used for constructing the graph.

2. This graph is replicated for time $t = 1$ to the maximum of deadlines of all the connections denoted by T.

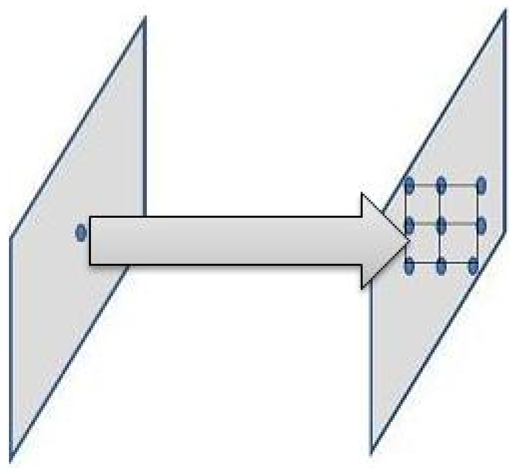

Figure 12: Range in the time expanded network

3. The node (i, j) at time $t = 0$ is connected to the node (k, l) if their manhattan distance is ≤ 1 in the same place as shown in figure 12.

4. The time expanded network consists of $T - 1$ time slices for times from $2....T$.

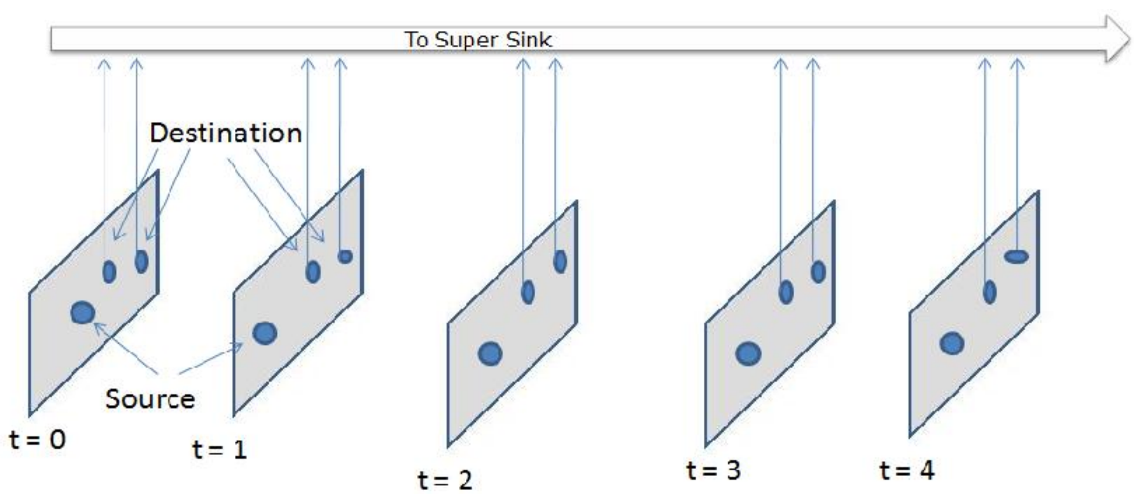

Figure 13: Time expanded network

5.2.3 Congestion Metric

We maintain some metrics on each node to track how busy or under-utilized they are. We also have developed a very simple metric for gauging the path congestions, for this real time application. Amongst the one or two or three nodes we have, the decision on the node to be used as the next hop for a particular connection between a source and a destination is based on its congestion metric. This is a weighted average of its node congestion metric and its path congestion metric.

5.2.3.1 Node Congestion Metric

The node congestion metric for a particular connection is calculated as the percentage of time it is likely to be congested because it is either sending or receiving data or it is in the interference region of other nodes sending or receiving data. The scope of time for analysis is from the start of a connection request to the connection deadline.

5.2.3.2 Path Congestion Metric

To capture the congestion in the likely paths leading to the destination, we consider the area that is the union of the rectangle formed by the source and destination using horizontal and vertical links in the grid, as well as the rectangle formed by the 45/135 degree lines through the source and destination. The weighted centroid of this area is found to be the sum of the product of the node congestion and its location. The next hop nodes that is closest to this weighted centroid is the one that is in higher congestion region. Hence the hop that is farthest from the centroid is the one that is chosen as the next hop for the connection.

5.2.4 Algorithm

1. The complete time expanded graph $G(V, E)$ is constructed as described in section 5.2.2.

2. The connection requests are sorted according to the metric as detailed in section 5.2.1. The connection with the highest priority is selected as the connection of interest.

3. All the destination nodes at each time slice are connected to the pipe connecting to the super sink.

4. For each arc from a source node at time t to the nodes in its transmission range at time $t + 1$, the connection cost is given a value of 1. For each arc from the destination node to the sink, the connection cost is deemed to be 0. The graph under consideration in the algorithm is a directed graph in the direction of increasing value of time.

5. In a copy of this original graph, all the portions of the graph beyond the deadline for the connection are removed. This new graph is denoted as $G(V', E')$.

6. The shortest path from the source to the supersink for this connection can be calculated using any popular algorithm like Dijkstra's algorithm using the graph $G(V', E')$. If the destination cannot be reached, skip to step 10.

7. If there is more than one destination, previous step will only find the shortest path for only one destination. To find the path to other destinations, all the nodes in the actual path in the time expanded path are connected to one super source. This super source is then used to find the shortest path to the other destination node. This technique is used to find the shortest path for all the destination nodes from the source in the connection. The union of the paths is recorded as part of the solution for the connection in the original graph $G(V, E)$.

8. In addition to the paths, the interference information is also recorded in the $G(V, E)$. In the time expanded network, when a connection from a node is carried forward to the next time slice, it denotes that the node is silent during that

time instant. When a connection is made from a node at time t to its neighbor at time t+1, it denotes occurrence of a transmission. When a transmission takes place, the arcs connected to all the nodes in the interference zones for the nodes in the shortest path are discarded.

9. All the arcs to the pipe from destinations of the current connection are removed.

10. The next connection to be allocated is picked. The pipe connection is added to the destinations. The step 5 is repeated till all connections are allocated .

5.2.5 Results

The algorithm was implemented for 802.11g and 802.11n networks. The image parameters(q) and the time of interest(t) was mapped for each of these WLANs as in 4. The topology consisted of $10x10$ grid with a total of 100 nodes. The connections were randomly generated. Since the distribution of the random number generator is uniform, this translates to an average of 5 hops per connection. Noting this is important for the analysis of results since for a two hop network, the throughput obtained during this simulation can be multiplied by $2^{(5-2)}$. For such two hop cases, when DL compression levels are used, the delivery of the entire image seems feasible even when large number of such requests are placed on the system.

The figures 16 and 17 show the percentage of the image that can be delivered within the 5 second delay deadline. This is an important metric since it can be used to calculate the percentage of image that can be allocated to each ROI based on the level of compression acceptable to the user. It is noticed that this amount decreases with increase in the number of connection in the network. For instance, when ten connection request are made each transmitting 10MB sized image, 90% of the image in the uncompressed form get delivered to the destination on an average within the delay deadline. If the user requests all of the image to be delivered to the receiver, and does not mind some compression, then ML can be used to compress a portion of

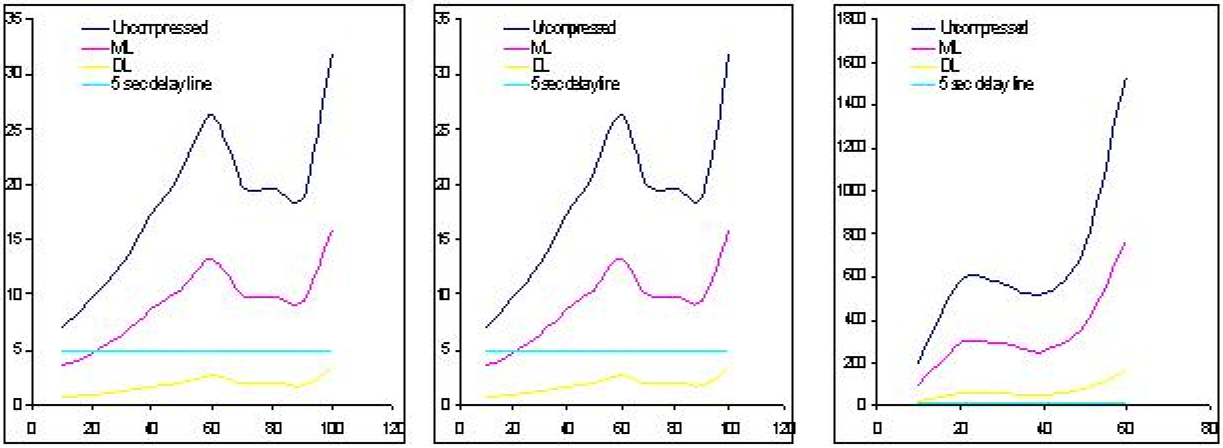

Figure 14: Average delay for delivery of images for each connection in a 5-hop network in a 802.11g system for sizes (a) 10MB, (b) 100MB, (c) 1000MB

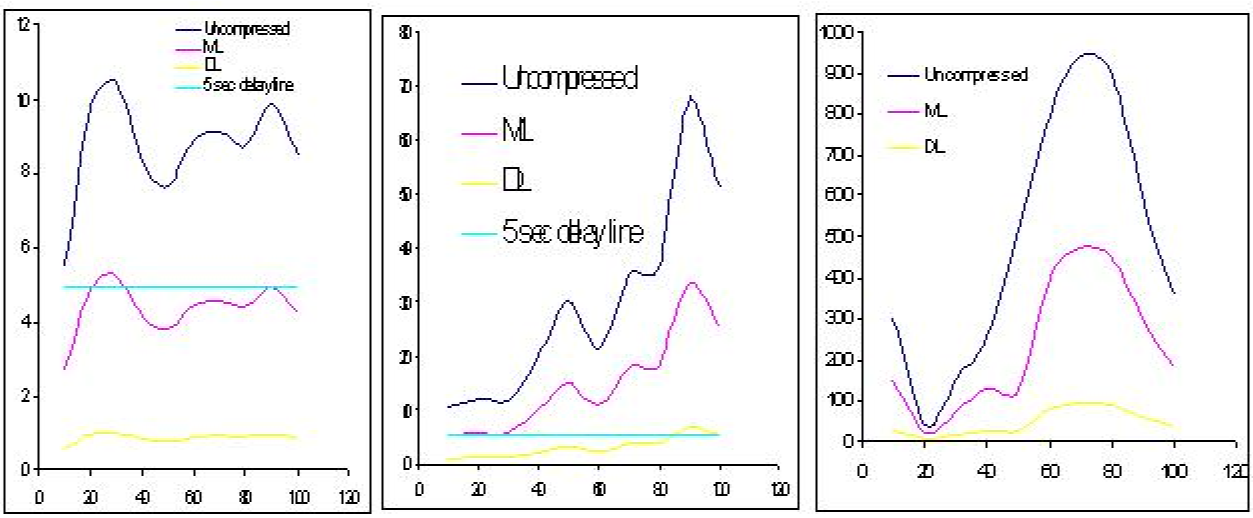

Figure 15: Average delay for delivery of images for each connection in a 5-hop network in a 802.11n system for sizes (a) 10MB, (b) 100MB, (c) 1000MB

the image before transmission.

The simulation results show that, when the latest WLAN technologies and compression methodologies are exploited to the fullest by using 802.11n and diagnostically lossless compression technique, even high connection demands like 100 connections in a 100 node grid topology can be met within the time deadline of 5 seconds.

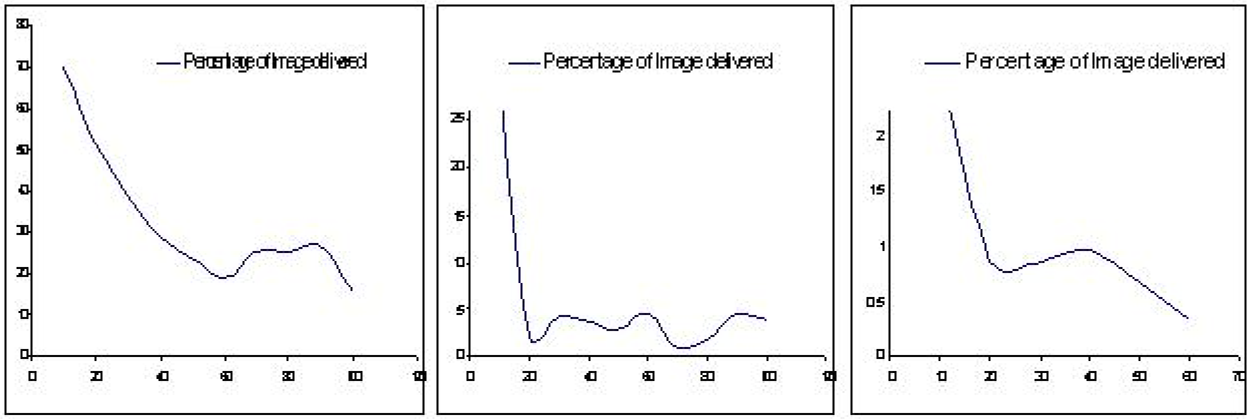

Figure 16: Percentage of image delivered before the deadline in 802.11n network for image of size (a) 10MB, (b) 100MB, (c) 1000MB

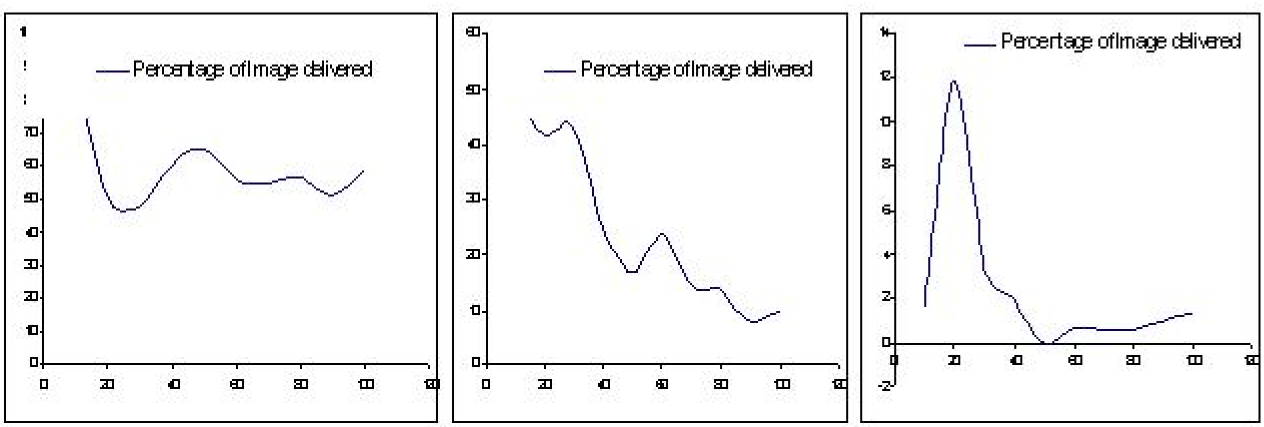

Figure 17: Average amount of image delivered before the deadline in 802.11n network for image of size (a) 10MB, (b) 100MB, (c) 1000MB

CHAPTER VI

CONCLUSION

Due to the richness of content in medical images and its requirement of strictly lossless transmission, we found that even after compressing the image using the diagnostically lossless methodology, the entire image could not be delivered to the destination nodes within the delay deadline for rich images. This was the case for most cases, even for the topologies that used 802.11n as their underlying network technology. Due to this, only the regions of interest of the image are transmitted to the destination nodes. In order to maximize the percentage of image transmitted in a resource constrained network, multi-commodity flow approach is used to model the system and generate the optimal value. However, these being NP hard, cannot be used in a dynamic network. Using the initial solution obtained from mathematical modeling, addition image delivery within the deadline is performed by a greedy algorithm that is fast and near optimal.

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